

Interdisciplinary Applications of Autonomous Observation Systems

Marlon R. Lewis
Satlantic, Inc.
Richmond Terminal, Pier 9, 3295 Barrington Street
Halifax, Nova Scotia, Canada B3K 5X8
phone: (902) 492-4780 fax: (902) 492-4781 email: marlon@satlantic.com

John J. Cullen
Department of Oceanography, Dalhousie University
Halifax, Nova Scotia, Canada B3H 4J1
phone: (902) 494-6667 fax: (902) 494-2039 email: John.Cullen@Dal.CA

Contract # N0001406C0030
<http://www.satlantic.com>

LONG-TERM GOALS

Our long-term goal is to develop improved autonomous observation systems and analytical capabilities for describing the distributions and activities of marine microbes in relation to their physical, chemical and optical environment in support of multidisciplinary, data-assimilating predictive models of optical and biological processes in the world ocean.

OBJECTIVES

Our primary objectives are:

- To develop and test new interdisciplinary sensor arrays on a variety of *in situ* platforms to describe biological variability in relation to the optical, physical and chemical environment of the ocean; and
- To use data from these sensor systems in multidisciplinary models of physically and chemically driven ocean biology.

APPROACH

Data from deployments of coastal ocean observatories and research cruises are used to develop and evaluate models and bio-optical algorithms for estimating optical and biological properties of surface waters using measurements from a variety of optical instruments. An extensive program of sampling from research vessels at our coastal observatories provides a large set of data for development and validation of bio-optical models for case 2 waters.

Several of our bio-optical analyses utilize chlorophyll fluorescence — sun-induced, or stimulated by a variety of fluorometers — to describe variability in the biomass or physiological status of phytoplankton. Consequently, we study the environmental influences on chlorophyll fluorescence in controlled laboratory experiments using different taxonomic groups of phytoplankton. The research

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 2008		2. REPORT TYPE		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE Interdisciplinary Applications of Autonomous Observation Systems				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Satlantic, Inc, Richmond Terminal, Pier 9, 3295 Barrington Street, Halifax, Nova Scotia, Canada B3K 5X8,				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 8	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

employs a careful characterization of Satlantic's Fluorescence Induction and Relaxation (FIRE) fluorometer, to define clearly its potential and limitations for describing phytoplankton physiology under a broad range of conditions. We are also working on reconciling spatial and temporal patterns in sun-induced fluorescence yield (assessable from space) with patterns of relative fluorescence yield detected with fluorometers at the surface and in the ocean interior. The objective is to link assessments of phytoplankton physiology from space to autonomous measurements from instruments such as ocean gliders and the physical/biological interactions that they describe.

More broadly, we are working within our own research group and with others in the ocean-observation community to develop effective new ways to make ocean observatory data easily accessible to a broad range of users and to explore new technologies for ocean monitoring (Babin et al. 2008, Lewis, 2008, Moore et al. 2008). Also, we are developing new approaches to facilitate advanced interdisciplinary, observation-based modeling of the ocean (Cullen et al. 2008).

This work is closely coordinated with the NSERC/Satlantic Industrial Research Chair in Environmental Observation Technology, a partnership between John Cullen (the Chair), Dalhousie University and Satlantic. The Research Chair facilitates a broad range of collaborative research, including funding of coastal observatories in Nova Scotia (see "Related Projects"). This ONR project provides funding for additional support from Satlantic which complements Dalhousie-based efforts.

WORK COMPLETED

Optical moorings and ground-truthing in coastal waters. We wrapped up our six-year program of research aimed at developing data-driven, interdisciplinary marine environmental forecasts in coastal waters of Nova Scotia (Cullen and Ritchie 2008). The data came from an ocean observatory in Lunenburg Bay, including three highly instrumented moorings with hyperspectral observations of upwelling radiance and downwelling irradiance; they also included multi-spectral K-chains, physical observations (currents, temperature, salinity profiles) and observations of meteorological variables. The systems communicated via wireless broadband to shore based computers at Dalhousie. The three moored systems in Lunenburg Bay functioned very well from 2002 - 2007 (except during winter haul-out and some interruptions), providing real time data supported by nearly weekly sampling for ground-truth data: vertical profiles of irradiance, fluorescence, spectral backscatter, dissolved and particulate absorption; and samples for chlorophyll, HPLC pigments, nutrients and particulate and dissolved absorption. A new optical profiler was assembled, tested and deployed for studies of optical properties; it includes fast sensors for temperature and conductivity, plus oxygen, backscatter, three types of fluorescence, a Satlantic in situ nitrate sensor and a WET Labs ac-s in situ spectrophotometer.

Redeployment of an optical mooring. Regrouping from the termination of our ocean observatory project, we refurbished and modified one of the Lunenburg buoys and established a strong collaboration with colleagues at the Bedford Institute of Oceanography to start a new program of observations, analysis, modeling and experimentation centered around the Bedford Basin Ocean Monitoring Buoy (BBOMB). The buoy is being deployed at the site of more than forty years of observations, including more than 14 years of weekly sampling (with a few interruptions) for physical, chemical and biological properties, including flow cytometric characterization of the microbial assemblage complemented by HPLC pigment analysis (Li and Harrison 2008). The time series, conducted by Dr. W.K.W. Li, is a tremendous resource that will now be complemented by continuous bio-optical assessment with weekly ground-truth sampling.

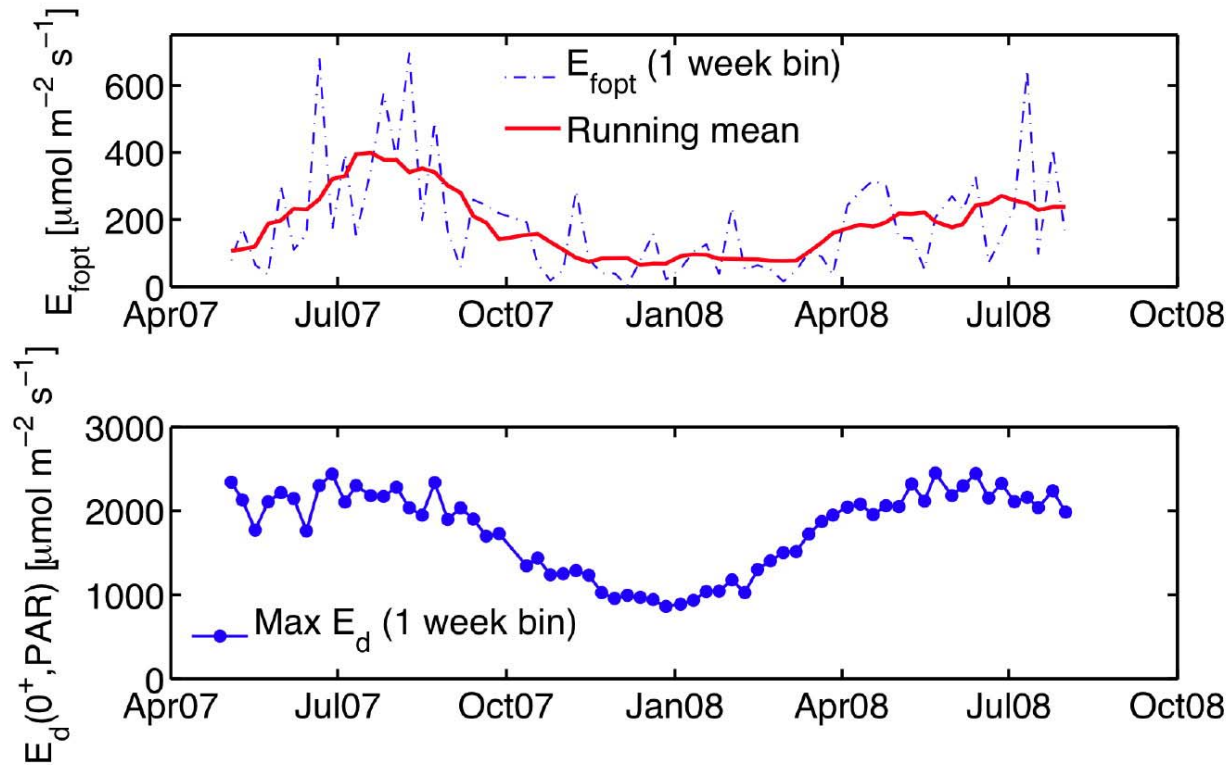


Figure 1. Assessing the annual cycle of acclimation of phytoplankton using data from an autonomous mooring. The Land Ocean Biogeochemical Observatory (LOBO) buoy measures diel variations in chlorophyll fluorescence at the sea surface that are related to variations of sunlight throughout the day/night cycle. By binning data for a week and examining the changes of fluorescence with respect to irradiance, a photoacclimation parameter of phytoplankton, $E_{f_{opt}}$ ($\mu\text{mol m}^{-2} \text{s}^{-1}$) is estimated. $E_{f_{opt}}$ is a measure of acclimation to irradiance that can be related mechanistically to the same processes that determine the saturation irradiance for photosynthesis E_k ($\mu\text{mol m}^{-2} \text{s}^{-1}$). However, more research is needed to establish the quantitative relationship between $E_{f_{opt}}$ and E_k . This time series from the Northwest Arm, Nova Scotia, demonstrates that the seasonal variability of $E_{f_{opt}}$ (upper panel) is well related to maximum weekly irradiance for May 2007 through August 2008 (lower panel), but other factors may be at play. Easy availability of records such as these will facilitate the development and testing of hypotheses about the environmental factors that determine the acclimation state of phytoplankton in surface layers. This information is central to the next generation of plankton models that depend on optical assessment of the physiological state of phytoplankton.

[Graph: $E_{f_{opt}}$ increases during the summer and decreases through the winter in a record from May 2007 through August 2008. The pattern of the weekly maximum surface irradiance is similar, but with differences in the late spring, when $E_{f_{opt}}$ increases while maximum irradiance is relatively steady and high.]

Land/Ocean Biogeochemical Observatory. We continued to analyze data from LOBO, the Land/Ocean Biogeochemical Observatory (Comeau et al. 2007), as the data record extended into its second year. Graduate student Adam Comeau quantified fluorescence quenching from day-night differences in the measurements of chlorophyll fluorescence to describe the annual cycle of acclimation to light as it relates to surface irradiance (Fig. 1).

Retrieval of physiological information using measurements from conventional fluorometers. As illustrated in Fig. 1, Adam Comeau analysed data from conventional fluorometers deployed on commonly used oceanographic profiling systems and novel systems (SeaHorse autonomous profiler and Satlantic's LOBO observatory) to retrieve estimates of $E_{f\text{ opt}}$, the irradiance at which fluorescence yield of phytoplankton in a light gradient is maximal (Comeau and Cullen 2008; Comeau et al. 2008). Our preliminary laboratory studies show a strong relation between $E_{f\text{ opt}}$ and E_k , the saturation irradiance for photosynthesis — a sensitive indicator of physiology (light acclimation status) and also a key parameter in models of primary productivity. We are now continuing systematic investigations of the relationships between our fluorescence-based estimate of acclimation and environmental factors.

Reconciling variability in different measures of fluorescence yield. Relying on published studies and a recently refined quantitative framework for interpreting spatial and temporal variation of near-surface sun-induced chlorophyll fluorescence yield as a function of irradiance (Schallenberg et al. 2008), Susanne Craig and colleagues examined sun-induced chlorophyll fluorescence at the surface and in vertical profiles to explore what the dramatic variability of fluorescence yield observed from space is telling us about phytoplankton physiology and its forcing factors (Craig et al. 2008). In turn, John Cullen and colleagues are constructing a framework for incorporating optically derived proxies for physiological properties into models of phytoplankton dynamics in the ocean (Cullen et al. 2008).

Interdisciplinary modeling. Efforts to develop observation-based interdisciplinary modeling systems advanced. Maud Guarracino and colleagues integrated her bio-physical modeling system into a multiply-nested, high-resolution forecast system for Lunenburg Bay (Guarracino et al. 2008) and ran it during the final season of the project. We learned what it takes to assemble a real-time bio-physical forecast system. As we move on to new projects, a collaboration with Dalhousie's Katja Fennel has been established, and now graduate student Diego Ibarra is using the ROMS modeling platform to model coastal ecosystems influenced by shellfish aquaculture.

RESULTS

Published research over 40 years on the variability of chlorophyll fluorescence yield in the ocean is relevant to new data streams from autonomous ocean sensor systems such as gliders (Sackmann et al. 2008; Cullen 2008). And novel research is needed to answer questions that are key to interpreting the observed variability. We are trying to contribute to the foundations of new oceanographic applications of fluorescence in the form of a comprehensive and quantitative framework for describing and interpreting natural variability in the quantum yield of chlorophyll fluorescence in the ocean — both sun-induced chlorophyll fluorescence as measured with radiometers, and fluorescence measured with conventional and advanced (e.g., FIRE) fluorometers. This has significant implications for retrieving information on the physiological status of phytoplankton in the sea, and year by year we feel that we are making solid, incremental progress. We now have the tools to use measurements of fluorescence, spectral irradiance and optical proxies of biomass (e.g., attenuation, backscatter) to describe fluorescence yield vs irradiance in the ocean, and to ascribe variations with depth and time to fundamental photophysiological processes. Ultimately, this will allow us to move much closer to

observation based descriptions of the influence of environmental factors on the photosynthesis and growth rates — hence the population dynamics — of phytoplankton in the sea. And this is the foundation of describing particle dynamics and biologically produced optical variability in the ocean.

IMPACT/APPLICATIONS

Coastal observatories. Our coastal observatory project is over after six years. We integrated the system, produced forecasts, and presented the information on line. The system is neither mature nor fully capable, but it represents very significant accomplishments in the development of ocean observatories. We know exactly what it takes to run a coastal observation and forecast system. This information is critical in planning for new systems and an integrated ocean observing strategy. We are happy to share our knowledge (e.g., as Cullen did in response to an invitation from the Venice Water Authority) and will continue to do so. A scaled-down ocean observatory in Bedford Basin Nova Scotia will carry on the research related to this project, complementing a long-term monitoring program conducted by the Canadian Department of Fisheries and Oceans (Li and Harrison 2008).

The book on Real-time Coastal Observing Systems for Marine Ecosystem Dynamics and Harmful Algal Blooms: Theory, Instrumentation and Modelling, delayed for years at UNESCO press, was finally published. Chapters were written to complement a highly successful workshop in 2003. Delays were beyond the control of editors Marcel Babin, Collin Roesler and John Cullen.

Fluorescence. We continue to develop a quantitative and comprehensive framework for interpreting measurements of chlorophyll fluorescence with the expectation that research using interpretations of chlorophyll fluorescence will expand. With the development of new fluorometers for ocean gliders and presentations at scientific meetings about physiological interpretations of fluorescence as measured from space, there is a need for quantitative, experimentally based interpretations, and we feel that our research will contribute to that.

New directions in interdisciplinary oceanography. Cullen's contributions to new directions in marine science were recognized with a third invitation to be a visiting faculty member for the Agouron Institute Hawaii Summer Course, "Microbial Oceanography: From Genomes to Biomes". It was an opportunity to interact with future leaders in ocean science (the students, who were selected through competition) and the cutting-edge researchers who are bringing genomics research to oceanography today. He also contributed in several ways to the intensifying debate about fertilization of the ocean for carbon offsets (Invited presentations for the twentieth anniversary of the International Geosphere-Biosphere Programme, a major symposium at WHOI, and a special thematic section for Marine Ecology Progress Series) and served on a small task force to identify key question on oceans for the Canadian Institute for Advanced Research.

TRANSITIONS

Software for analysis of data from Satlantic's FIRE fluorometer — FIREworx — developed by Audrey Barnett, was improved, shared with Satlantic engineers, and made freely available to users of the FIRE.

RELATED PROJECTS

1) NSERC/Satlantic Industrial Research Chair: this partnership is the focus of support for Cullen's research activities. Funding for complementary projects, such as this ONR program, are highly

leveraged by the research partnership and associated grants. This project funded the refurbishment and redeployment of the Bedford Basin Ocean Monitoring Buoy to be incorporated into a long term sampling program led by Dr. W.K.W. Li at the Bedford Institute of Oceanography (Li and Harrison 2008).

2) A research project on interdisciplinary marine environmental prediction in the Atlantic coastal zone (Canadian Foundation for Climate and Atmospheric Sciences) has been a major source of support for the field program in Lunenburg Bay and the development of optical data products for use in models of the Bay. The Lunenburg Bay infrastructure was funded by the Canada Foundation for Innovation, Nova Scotia, and several other partners. It supported the initial development of the Data Access and Visualization project. The project is now complete.

3) ONR-funded research by Marlon Lewis and colleagues related to the variation in the optical properties of the upper ocean and the influence on the radiance distribution (see Van Dommelen et al. 2008; Zhang et al. 2008).

4) A research project funded by Cellana BV is aimed at screening strains of microalgae for their potential to produce next-generation biofuels and protein. The project provided funds for new equipment, and leverages fundamental research on fluorescence.

REFERENCES

- Comeau, A. J., Cullen, J. J. 2008. New method to estimate a parameter of phytoplankton physiology related to primary productivity models. ASLO Summer Meeting, St. John's NL, Canada, June 2008.
- Comeau, A.J., S.E. Craig, M. Babin, M. Lewis, F. Bruyant, and J.J. Cullen. 2008. Variations of photoacclimation related to environmental conditions. 2008. Ocean Optics XIX, Oct 6 - Oct 10, Barga, Italy.
- Comeau, A.J., M.R. Lewis, J.J. Cullen, R.S. Adams, J. Andrea, S. Feener, S.D. McLean, K.S. Johnson, L.J. Coletti, H.W. Jannasch, S.E. Fitzwater, C. Moore, and A.H. Barnard. 2007. Monitoring the spring bloom in an ice covered fjord with the Land/Ocean Biogeochemical Observatory (LOBO). MTS/IEEE Oceans 2007, doi: 10.1109/OCEANS.2007.4449185.
- Cullen, J.J., A. Comeau, S.E. Craig, R.F. Davis, K. Fennel. 2008. On the use of optical measurements to constrain models of marine primary productivity and particle dynamics. Ocean Optics XIX, Oct 6 - Oct 10, Barga, Italy.
- Cullen, J.J. and H. Ritchie. 2008. Life cycle of an ocean observatory: The Lunenburg Bay Project. Ocean Sciences Meeting, Orlando, March 2008.
- Craig, S.E., Comeau, A., Cullen, J.J. 2008. The effects of physical forcing on stimulated chlorophyll fluorescence reveals the influence of ocean interior processes on the quantum yield of sun-induced chlorophyll fluorescence. Ocean Optics XIX, Barga, Italy.
- Ibarra, D. A., Hasegawa, D., Fennel, K., Cullen, J. J. 2008. Water-column impacts of bivalve aquaculture: bio-optical assessment and 3-D modeling in a mussel farm in Ship Harbour, Nova Scotia. ASLO Summer Meeting, St. John's NL, Canada, June 2008.

- Li, W. K. W., and W. G. Harrison (2008), Propagation of an atmospheric climate signal to phytoplankton in a small marine basin, *Limnol. Oceanogr.*, 53(5), 1734-1745.
- Moore, C., A. Barnard, P. Fietzek, M.R. Lewis, H.M. Sosik, S. White, and O. Zielinski 2008. Optical tools for ocean monitoring and research. In, *Ocean Sensors*, [refereed, in press].
- Sackmann, B. S., M. J. Perry, and C. C. Eriksen. 2008. Seaglider observations of variability in daytime fluorescence quenching of chlorophyll-a in Northeastern Pacific coastal waters, *Biogeosciences Discuss.*, 5, 2839-2865.
- Van Dommelen, R., J. Wei, K. Voss, S. McLean, and M. Lewis. 2008. Initial results from RADCAM, a high dynamic range radiance camera. *Ocean Optics XIX*, Barga, Italy.
- Zhang, X., M. Twardowski, C. Hu, and M. Lewis. 2008. Retrieve size and optical properties of individual particle populations from the volume scattering function. *Ocean Optics XIX*, Barga, Italy.

PUBLICATIONS

The following manuscripts resulted in full or in part from this contract:

- Claustre, H., Y. Huot, I. Obernosterer, B. Gentili, D. Tailliez and M. Lewis 2008. Gross community production and metabolic balance in the South Pacific Gyre, using a non-intrusive bio-optical method. *Biogeosciences*, 5, 463-474. [refereed]
- Cullen, J.J. 2008. Interactive comment on “Seaglider observations of variability in daytime fluorescence quenching of chlorophyll-a in Northeastern Pacific coastal waters” by B. S. Sackmann et al. *Biogeosciences Discuss.*, 5, S1481–S1491, 2008.
- Cullen, J.J. 2008. Observation and prediction of harmful algal blooms. In: Babin, M., Roesler, C.S., and Cullen, J.J. (eds), *Real-time Coastal Observing Systems for Marine Ecosystem Dynamics and Harmful Algal Blooms: Theory, Instrumentation and Modelling*. UNESCO, Paris. [refereed, invited]
- Cullen, J.J. and P. W. Boyd. 2008. Predicting and verifying the intended and unintended consequences of large-scale ocean fertilization. *Marine Ecology Progress Series* 364: 295-301, doi:10.3354/meps07551 [refereed, invited]
- Guarracino M, Dowd M, Sheng J, Cullen JJ. 2008. Development of a coupled biological-physical model appropriate for real-time prediction in a coastal inlet. *Journal of Marine Systems* (refereed; in revision)
- Lewis, M.R. 2008. The measurement of apparent optical properties for the diagnosis of harmful algal blooms. In: Babin, M., Roesler, C.S., and Cullen, J.J. (eds.), *Real-time Coastal Observing Systems for Marine Ecosystem Dynamics and Harmful Algal Blooms: Theory, Instrumentation and Modelling*. UNESCO, Paris. [refereed]
- Prasil O., D. J. Suggett, J. J. Cullen, M. Babin and Govindjee (2007). Aquafluo 2007: chlorophyll fluorescence in aquatic sciences, an international conference held in Nové Hradý. *Photosynthesis Research* DOI 10.1007/s11120-007-9234-5.

Schallenberg, C., M. R. Lewis, D. E. Kelley, and J. J. Cullen. 2008. Inferred influence of nutrient availability on the relationship between Sun-induced chlorophyll fluorescence and incident irradiance in the Bering Sea, *J. Geophys. Res.*, 113, C07046, doi:10.1029/2007JC004355. [refereed]

Stramski, D., R.A. Reynolds, M. Babin, S. Kaczmarek, M.R. Lewis, R. Rottgers, A. Sciandra, M. Stramska, M.S. Twardowski, and H. Claustre 2008.: Relationships between the surface concentration of particulate organic carbon and optical properties in the eastern south pacific and eastern atlantic oceans, *Biogeosciences*, 5, 171–201. [refereed]

Book (co-editor)

Babin, M., Roesler, C.S., and Cullen, J.J. (eds). 2008. Real-time Coastal Observing Systems for Marine Ecosystem Dynamics and Harmful Algal Blooms: Theory, Instrumentation and Modelling. UNESCO, Paris. 866 pp. [refereed]

HONORS/AWARDS/PRIZES

Lewis was appointed Issac Walton Killam Professor, Dalhousie University.